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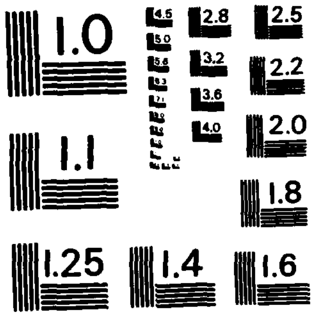

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FORWARD MULTIPLE SCATTERING CORRECTIONS AS FUNCTION OF DETECTOR FIELD OF VIEW

by

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June 1983

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The theoretical formulations are given for an approximate method based on the solution of the radiative transfer equation in the small angle approximation. The method is approximate in the sense that an approximation is made in addition to the small angle approximation. Numerical results were obtained for multiple scattering effects as functions of the detector field of view, as well as the size of the detector's aperture for three different values of the optical depth (τ) (= 1.0, 4.0 and 10.0). Three cases of aperture size were considered -- namely, equal to or

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20. ABSTRACT (Cont'd)

smaller or larger than the laser beam diameter. The contrast between the on-axis intensity and the received power for the last three cases is clearly evident.

PREFACE

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FORWARD MULTIPLE SCATTERING CORRECTIONS AS FUNCTION OF DETECTOR FIELD OF VIEW

I. INTRODUCTION

Low visibility atmospheric conditions occur in the presence of heavy concentrations of atmospheric aerosols such as dust, smoke and fog. Scattering of laser radiation by such aerosol clouds, being basically a multiple scattering process, is very difficult to predict. A fruitful approach to the problem has been a Monte Carlo technique, because it can handle strange geometries as well as inhomogeneities[1-3]. Recently, considerable attention has been paid to analytical solutions to the equation of transfer in a form appropriate for the laser beam propagation problem[4-9]. Although exact solutions have not been obtained to date, there are some special cases where simple and useful approximate solutions to the equation of transfer are available. For tenuous distribution of scatterers, the first-order multiple scattering theory can be used, and for dense distribution the diffusion approximation is appropriate. If the particle size is large compared with incident wavelength, the energy scattered by the particle is largely confined within a small angle in the forward direction and, therefore, by employing the small-angle approximation it is possible to simplify the equation of transfer. In Ref. 8, a systematic study of contributions of increasing order of scattering for both realistic and model aerosols has been conducted.

As indicated by Ishimaru[10,11], the first-order multiple scattering approximation is applicable when the density of scatterers is so low that the diffuse (incoherent) intensity is considerably smaller than the reduced (coherent) intensity. This will certainly be the case if optical distance traversed by the beam is much smaller than unity. However, the same weak fluctuation case is also encountered in the situations where the receiver has a narrow receiving angle. In this case, the amount of scattered intensity entering into the receiver is small compared with the direct coherent intensity, and therefore the received field is predominantly coherent. The effect of the detector's finite field of view on the received power has been a subject of comprehensive investigations related to forward scattering corrections for optical extinction measurements[12-17].

The purpose of this paper is to study the effect of a finite field of view on the intensity and the received power of a laser beam undergoing multiple scattering. Our analytic approach is based on the theory of Dolin[18] and Fante[19-22], summarized in Section II. In Sections II and IV, we apply this theory to Gaussian beams. Numerical results relevant to the beam propagation in a water cloud and model aerosol particles are presented in Section V.

II. THE FANTE-DOLIN THEORY

Our considerations will be based on the equation of radiative transfer for the radiance (specific intensity) distribution function, $I(\vec{\phi},\vec{r},z)$. In the small angle approximation, $I(\vec{\phi},\vec{r},z)$ satisfies

$$\vec{\phi} \cdot \frac{\partial I}{\partial \vec{r}} + \frac{\partial I}{\partial z} + \sigma I = \sigma_s \int P(\vec{\phi} - \vec{\phi}')\ I(\vec{\phi}',\vec{r},z)\ d\,\vec{\phi}' \qquad (1)$$

where σ and σ_s are volume extinction and scattering coefficients (m^{-1}) for the aerosol medium; $\vec{r}$ is the component of the position vector transverse to the z axis; and $\vec{\phi}$ is the transverse component of the unit propagation vector (Fig. 1 in Refs. 8 and 9).

In the work of Dolin[18] and Fante[19-22], which applies to sharply peaked phase functions, $I(\vec{\phi}',\vec{r},z)$ in the integrand on the right hand side of Eq. (1) is expanded in Taylor series about $\vec{\phi}' = \vec{\phi}$. More precisely, $I(\vec{\phi},\vec{r},z)$ is split into

$$I(\vec{\phi},\vec{r},z) = I^{(o)}(\vec{\phi},\vec{r},z) + I^{(s)}(\vec{\phi},\vec{r},z) \tag{2}$$

where superscripts o and s refer to unscattered and scattered radiance, respectively. Then, one expands

$$\begin{aligned} I^{(s)}(\vec{\phi},\vec{r},z) &= I^{(s)}(\vec{\phi},\vec{r},z) \\ &+ \sum_k (\phi' - \phi)_k \frac{\partial}{\partial \phi_k} I^{(s)}(\vec{\phi},\vec{r},z) \\ &+ \frac{1}{2} \sum_k \sum_\ell (\phi' - \phi)_k (\phi' - \phi)_\ell \frac{\partial^2}{\partial \phi_k \partial \phi_\ell} I^{(s)}(\vec{\phi},\vec{r},z) + \ldots \end{aligned} \tag{3}$$

where k and ℓ refer to the Cartesian components of the $\vec{\phi}$ vector. Recall that $\vec{\phi} = \phi_x \hat{x} + \phi_y \hat{y}$.

Equation (1) now yields

$$\vec{\phi} \cdot \frac{I^{(o)}}{\partial \vec{r}} + \frac{\partial I^{(o)}}{\partial z} + \sigma I^{(o)} = 0 \tag{4}$$

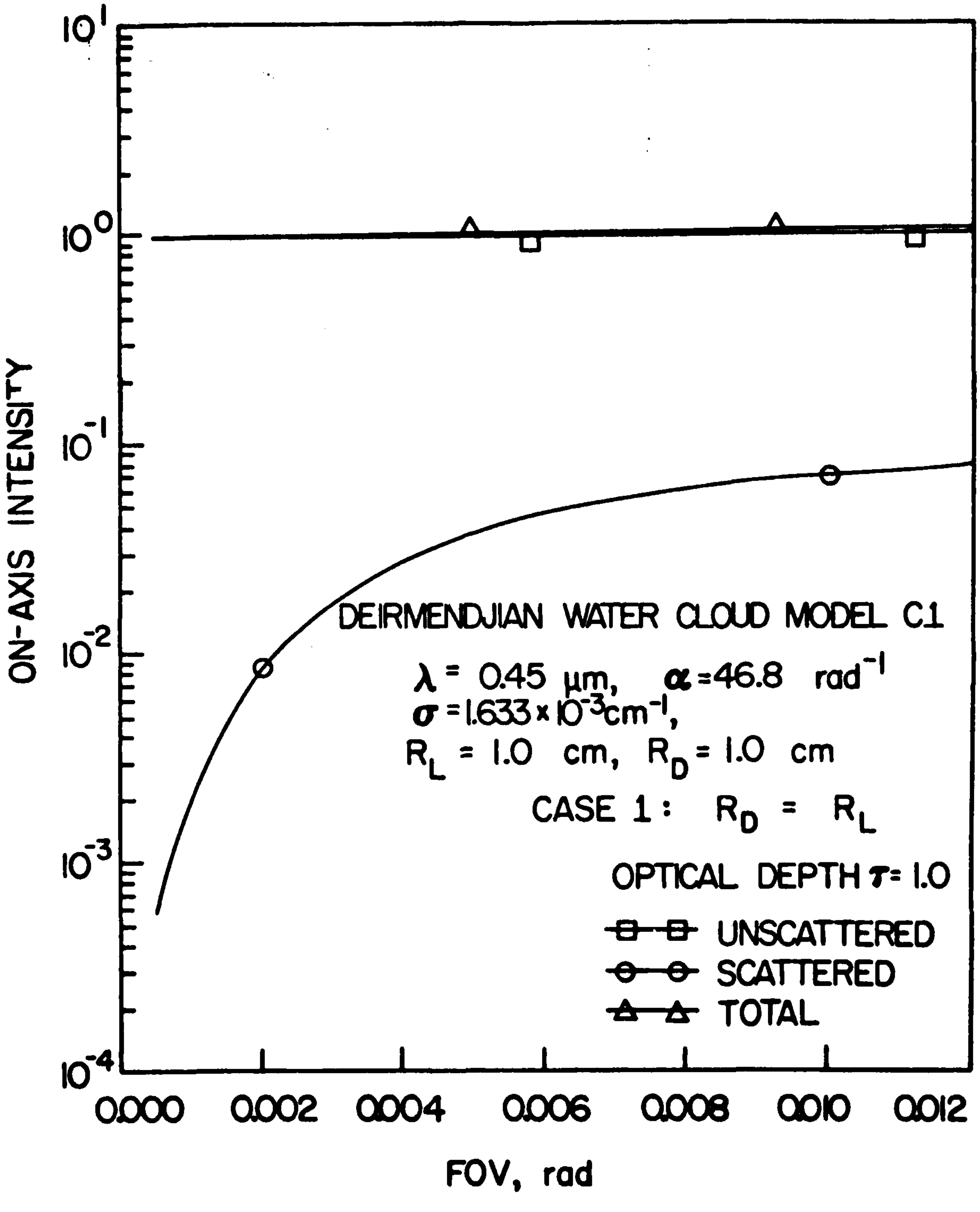

Figure 1. Normalized intensity on the beam axis as function of detector FOV corresponding to α = 46.80 rad^{-1}, R_D = 1.0 cm, and τ = 1.0.

while $I^{(s)}$ is determined from the nonhomogeneous equation

$$\vec{\phi} \cdot \frac{\partial I^{(s)}}{\partial \vec{r}} - \frac{\sigma\omega}{4} \langle \phi^2 \rangle \nabla_{\phi}^2 I^{(s)} + \frac{\partial I^{(s)}}{\partial z}$$

$$+ \sigma(1 - \omega)\, I^{(s)} = \sigma\omega \int P(\vec{\phi} - \vec{\phi}')\, I^{(o)} \, (\vec{\phi}', \vec{r}, z)\, d^2\phi' \qquad (5)$$

where $\omega = \sigma_s/\sigma$ is the single scattering albedo; and $\langle \vec{\phi}^2 \rangle$ is defined as

$$\langle \vec{\phi}^2 \rangle = \int P(\vec{\phi})\, \vec{\phi}^2\, d^2\phi \qquad (6)$$

In deriving Eq. (5) we have neglected the terms of higher order than second in Eq. (3). The solutions to Eqs. (4) and (5) can be obtained by the method of characteristics in the Fourier space of the variables $\vec{\phi}$ and $\vec{r}$. With the Fourier transforms defined generically as

$$\hat{I}(\vec{\xi}, \vec{\eta}, z) = \iint_{-\infty}^{\infty} d^2\phi\, d^2r\, I(\vec{\phi}, \vec{r}, z)\, e^{i(\vec{\xi}\cdot\vec{\phi} + \vec{\eta}\cdot\vec{r})} \qquad (7)$$

$$\hat{P}(\vec{\xi}) = \int_{-\infty}^{\infty} d^2\phi\, P(\vec{\phi})\, e^{i\vec{\xi}\cdot\vec{\phi}} \qquad (8)$$

we obtain the following solutions

$$\hat{I}^{(o)}\,(\vec{\xi}, \vec{\eta}, z) = \hat{I}(\vec{\xi} + \vec{\eta}z, \vec{\eta}, z = 0)\, e^{-\sigma z} \qquad (9)$$

and

$$\hat{I}^{(s)}\,(\vec{\xi}, \vec{\eta}, z) = \hat{I}(\vec{\xi} + \vec{\eta}z, \vec{\eta}, z = 0) \int P[\vec{\xi} + \vec{\eta}(z - z')]\, e^{-\sigma z}$$

$$\cdot \exp\left\{ - \int_{z'}^{z} [\frac{\sigma\omega}{4} \langle \vec{\phi}^2 \rangle\, |\vec{\xi} + \vec{\eta}\,(z - z'')|^2 + \sigma(1-\omega)]\, dz'' \right\} dz' \qquad (10)$$

for the unscattered and scattered contributions, respectively.

III. CASE OF COLLIMATED GAUSSIAN BEAM

We assume now that in the single scattering theory the scattering phase function $P(\vec{\phi})$ is given by a Gaussian function, i.e.,

$$P(\vec{\phi}) = \frac{\alpha^2}{\pi} \exp(-\alpha^2 \vec{\phi}^2) \tag{11}$$

and that the incident collimated beam, directed along the z axis, has a Gaussian spatial form, i.e.,

$$I(\vec{\phi},\vec{r},z=0) = F_o \pi^{-1} \gamma^2 \delta^{(2)}(\vec{\phi}) \exp(-\gamma^2 \vec{r}^2) \tag{12}$$

where $\delta^{(2)}$ is the Dirac delta function.

In the situation modeled by Eqs. (11) and (12), we obtain, after performing the inverse Fourier transforms of Eqs. (9) and (10), the explicit formulas for $I^{(o)}(\vec{\phi},\vec{r},z)$ and $I^{(s)}(\vec{\phi},\vec{r},z)$. They read

$$I^{(o)}(\vec{\phi},\vec{r},z) = F_o \pi^{-1} e^{-\sigma z} e^{-\gamma^2 \vec{r}^2} \delta^{(2)}(\vec{\phi}) \tag{13}$$

and

$$I^{(s)}(\vec{\phi},\vec{r},z) = \frac{F_o \sigma\omega e^{-\sigma z}}{(2\pi)^2} \int dz' \, [4A(z')C(z') - B^2(z')]^{-1} \cdot \exp\left\{ -\frac{A(z')\vec{r}^2 - B(z')\vec{\phi}\cdot\vec{r} + C(z')\vec{\phi}^2}{4A(z')C(z') - B^2(z')} \right\} e^{\omega\sigma z'} \tag{14}$$

where the functions A, B, and C are defined as

$$A(z') = \frac{1 + \sigma\omega z'}{4\alpha^2}$$

$$B(z') = \frac{2z' + \sigma\omega z'^2}{4\alpha^2}$$

$$C(z') = \frac{1}{4\gamma^2} + \frac{z'^2 + \sigma\omega z'^3/3}{4\alpha^2} \tag{15}$$

In polar coordinates (θ, b), the vector $\vec{\phi}$ can be expressed by

$$\phi_x = \theta \cos b$$

$$\phi_y = \theta \sin b \tag{16}$$

For a detector having the field of view (FOV) half-angle, θ_D, the received intensity is obtained from Eq. (14) after integration over the angle b in the range $(0, 2\pi)$ and over θ in the range $(0, \theta_D)$. The received intensity $F^{(s)}(\theta_D, \vec{r}, \sigma z)$ corresponding to the scattered beam thus becomes

$$F^{(s)}(\theta_D, \vec{r}, \sigma z) = \int_0^{\theta_D} I^{(s)}(\theta, \vec{r}, \sigma z)\theta \, d\theta \tag{17}$$

where

$$I^{(s)}(\theta, \vec{r}, \sigma z) = \frac{F_o \omega \, e^{-\sigma z}}{2\pi} \int_0^{\sigma z} [4A(\frac{x}{\sigma})C(\frac{x}{\sigma}) - B^2(\frac{x}{\sigma})]^{-1}$$

$$\cdot \; I_o \; [\frac{\theta r \; B(x/\sigma)}{4A(x/\sigma)C(x/\sigma) - B^2(x/\sigma)}]$$

$$\cdot \; \exp \; [- \frac{A(x/\sigma) r^2 + C(x/\sigma) \; \theta^2}{4A(x/\sigma)C(x/\sigma) - B^2(x/\sigma)}] \; e^{\omega x} \, dx \tag{18}$$

Here I_o is the modified Bessel function of zeroth order, and x is a dimensionless integration variable.

The contribution coming from the unscattered part of the beam is

$$F^{(o)}(\theta_D, \vec{r}, \sigma z) = F_o \pi^{-1} \, e^{-\sigma z} \, e^{-\gamma^2 \vec{r}^2} \tag{19}$$

It is thus seen that the numerical results can be extracted from this theory in a rather simple manner by performing merely a double integration.

IV. CASE OF GENERAL GAUSSIAN BEAM

More generally, one can account both for the spatial and angular divergence of the laser beam assuming a Gaussian law of the form

$$I(\vec{\phi},\vec{r},z = 0) = F_o \beta^2 \gamma^2 \pi^{-2} \exp(- \beta^2 \phi^2 - \gamma^2 \vec{r}^2) \tag{20}$$

for the incident beam. Here, the parameter β describes the angular divergence.

By following exactly the same line of reasoning as in Section III, we obtain the following contributions $F^{(s)}(\theta_D,\vec{r},\sigma z)$ corresponding to the scattered beam, viz.,

$$F(s)(\theta_D,\gamma\vec{r},\sigma z) = \theta_D^2 \int_0^1 I^{(s)} (\theta'\theta_D,\gamma\vec{r},\sigma z)\ \theta'\ d\theta' \tag{21}$$

where

$$I^{(s)} (\theta,\gamma\vec{r},\sigma z) = F_o\ \omega\ \sigma z\ e^{-\sigma z}/2\pi$$

$$+ \int_0^1 \left[4A\{(x/\sigma)\ z\sigma\}\ C\{(x/\sigma)\ z\sigma\} - B^2\{(x/\sigma)\ z\sigma\}\right]^{-1}$$

$$+ I_o \left[\frac{\theta(\gamma\vec{r}) - B((x/\sigma)\ z\sigma)/\gamma}{4A\{(x/\sigma)\ z\sigma\}\ C\{(x/\sigma)\ z\sigma\} - B^2\{(x/\sigma)\ z\sigma\}}\right]$$

$$+ \exp\left[- \frac{(\gamma\vec{r})^2\ A((x/\sigma)\ z\sigma)/\gamma^2 + C((x/\sigma)\ z\sigma)\theta^2}{4A\{(x/\sigma)\ z\sigma\}\ C\{(x/\sigma)\ z\sigma\} - B^2\{(x/\sigma)\ z\sigma\}}\right]$$

$$+ \exp(\omega\ x\sigma\ z) \cdot dx' \tag{22}$$

and I_o is the modified Bessel function of zeroth order.

For the unscattered beam, we obtain

$$F^{(o)}(\theta_D, \gamma\vec{r}, \sigma z) = 2F_o \beta^2 \exp(-\sigma z)\, \theta_D^{\,2}/\pi$$

$$+ \int_0^1 \theta' \, d\theta' \, I_o\{2(\gamma/\sigma)\, \theta_D \theta' (\gamma r)\, \sigma z\}$$

$$+ \exp\{-(\gamma\vec{r})^2 - \left[(\gamma/\sigma)^2 (\sigma z)^2 + \beta^2\right] \theta_D^{\,2}\, \theta'^{\,2}\} \qquad (23)$$

The integrals in Eqs. (22) and (23) have limits 0 and 1. This choice of limits anticipates the use of Gaussian quadrature in numerical computation.

V. RESULTS AND DISCUSSIONS

The numerical values were obtained for the on-axis intensities as a function of θ_D, and the plots shown in Figs. 1-3 depict the unscattered (reduced) intensity (squares), scattered or diffuse intensity (circles), and total intensity (triangles) on the beam axis for optical depth $\tau = 1$, 4, and 10, respectively. A divergent beam with the parameters $\beta = 2\pi/(\gamma\lambda)$ and $\gamma = 1.0\ cm^{-1}$ is assumed to be propagating with the Deirmendjian water cloud[24] model C1. For $\lambda = 0.45\ \mu m$, the extinction coefficient is obtained from the Mie theory computations when a modified gamma distribution is taken from water cloud particle size distribution. One also obtained $\alpha = 46.80\ rad^{-1}$ for the Gaussian fit to the phase function. For a coaxial detector, with a diameter $R_D = 1.0$ cm, the same as the laser beam diameter, the intensity F becomes a function of θ_D and z. We normalize the intensities by dividing

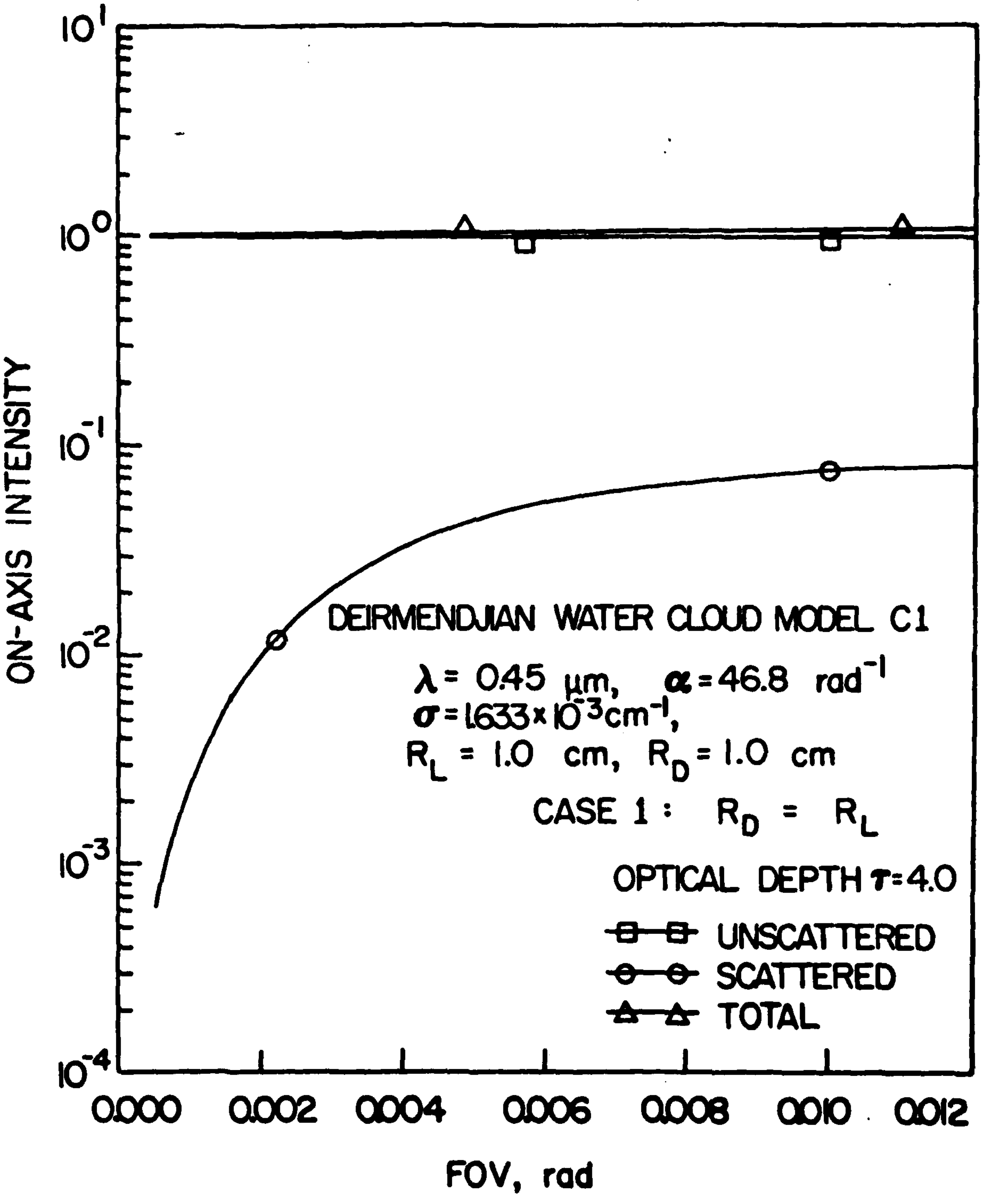

Figure 2. Normalized intensity on the beam axis as function of detector FOV corresponding to $\alpha = 46.80\ \text{rad}^{-1}$, $R_D = 1.0$ cm, and $\tau = 4.0$.

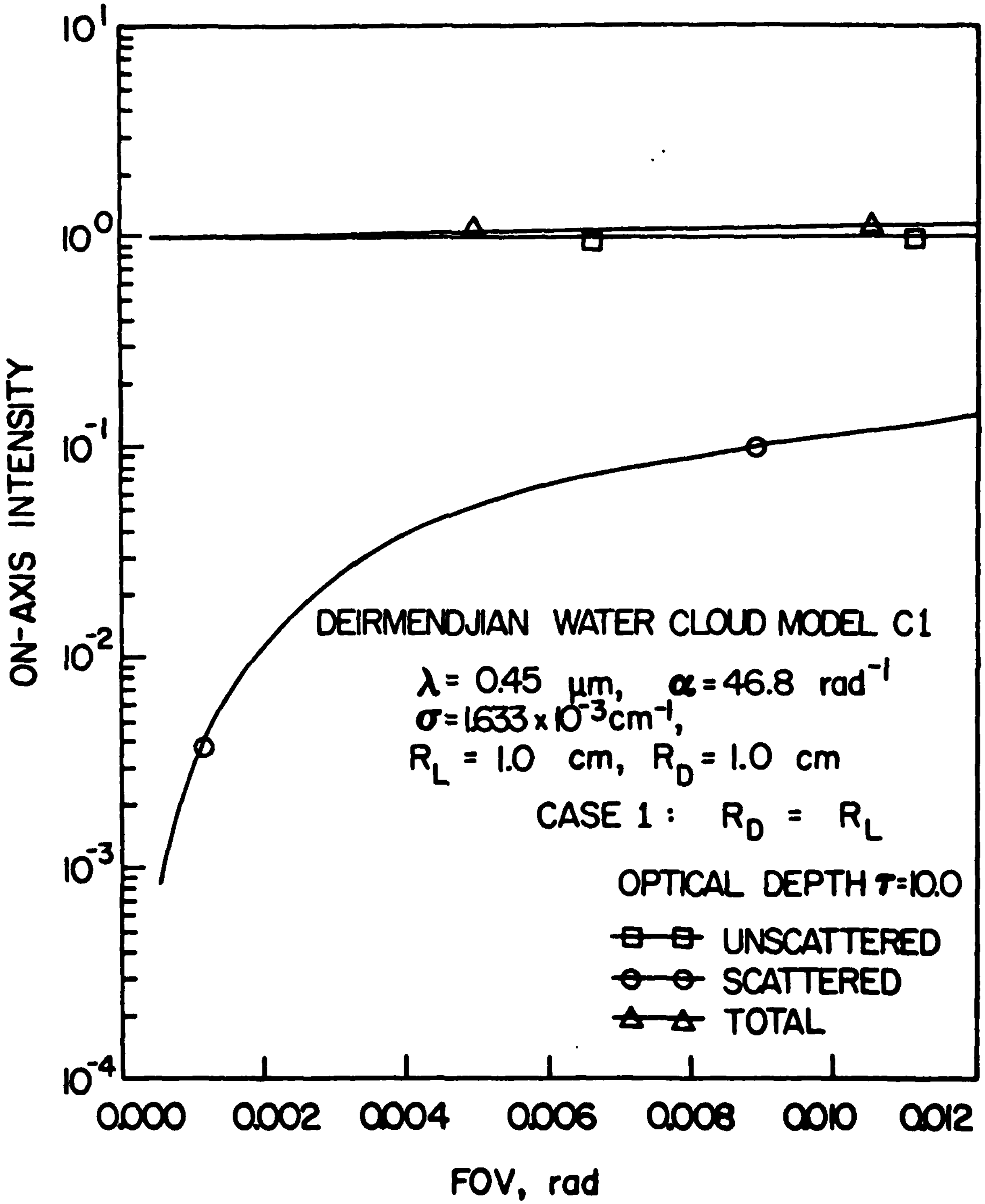

Figure 3. Normalized intensity on the beam axis as function of detector FOV corresponding to $\alpha = 46.80$ rad^{-1}, $R_D = 1.0$ cm, and $\tau = 10.0$.

out the factor $F^{(0)}(\theta_D = \infty, \; z = 0)$. For the sake of clarity in graphical presentation, we also scale the normalized intensities by the multiplicative factor $\exp(\tau)$.

In order to investigate the significance of the optical thickness, we calculated the power received by a coaxial detector of radius $R_D = 1$ cm. If $F(\theta_D, \vec{r}, \tau)$ denotes generically the beam intensity, then the received power is defined as

$$P\;(R_D) = 2\pi \int_0^{R_D} F(\theta_D, \vec{r}, \tau)\; r\; dr \tag{50}$$

The received power is also scaled by the multiplicative factor $\exp(\tau)$, and the power received at $z = 0$ is divided out. The numerical values were obtained for received power for a coaxial detector of diameter $R_D = 1$ cm, and the situation is depicted in Figs. 4-6 corresponding to the same parameters as in Figs. 1-4, respectively. As the FOV increases, both the intensity and the received power saturate rapidly, independently of the optical depth. This corresponds to the situation of an open detector. The contribution of the scattered power becomes dominant in the saturation region for optical depth of the order of 10.

Gaussian phase functions as given by Eq. (11) were best fitted in Ref. 8 to the exact Mie phase functions for monodisperse aerosols with radii in the range from 2.01 to 40.2 μm. In Figs. 7-9, we show the intensity vs. detector's FOV. In addition, we show the received power vs. FOV for $\tau = 4.0$ (Fig. 10). These sets of results were computed for the model particles characterized by the parameters $\quad = 289.33\ \text{rad}^{-1}$, and

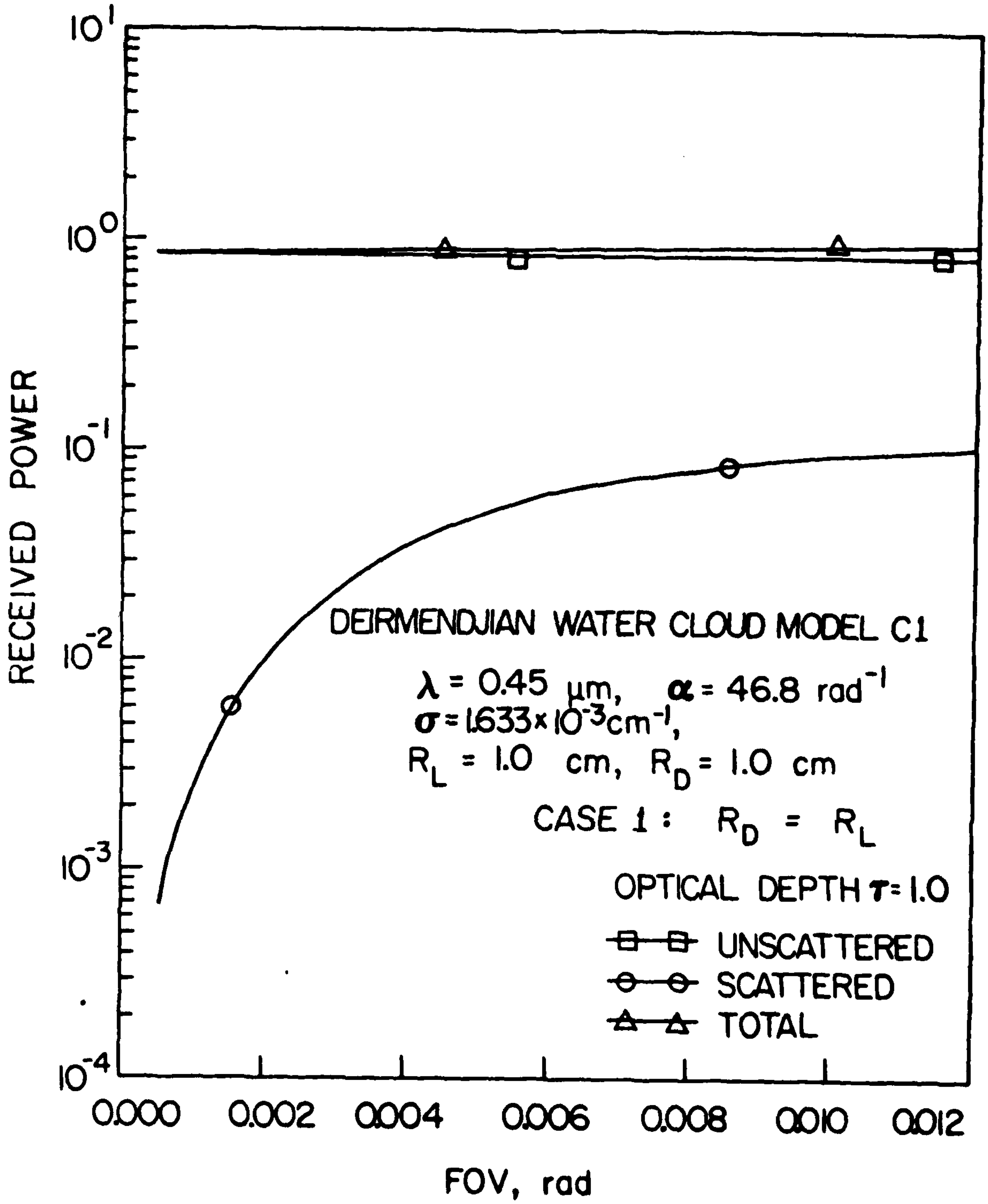

Figure 4. Received power (arbitrary units) on the beam axis as function of detector FOV corresponding to α = 46.80 rad^{-1}, R_D = 1.0 cm, and τ = 1.0.

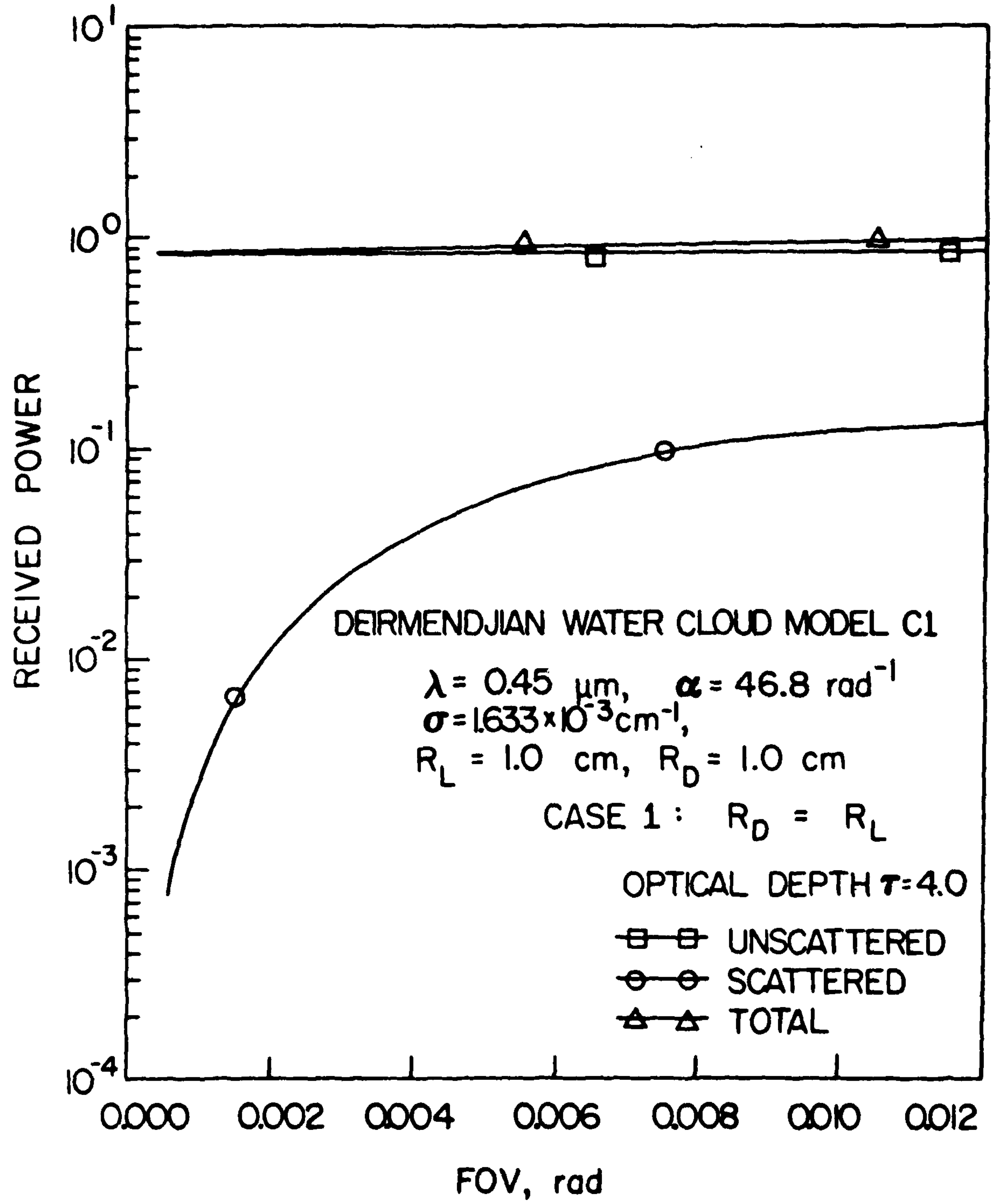

Figure 5. Received power (arbitrary units) on the beam axis as function of detector FOV corresponding to $\alpha = 46.80\ rad^{-1}$, $R_D = 1.0$ cm, and $\tau = 4.0$.

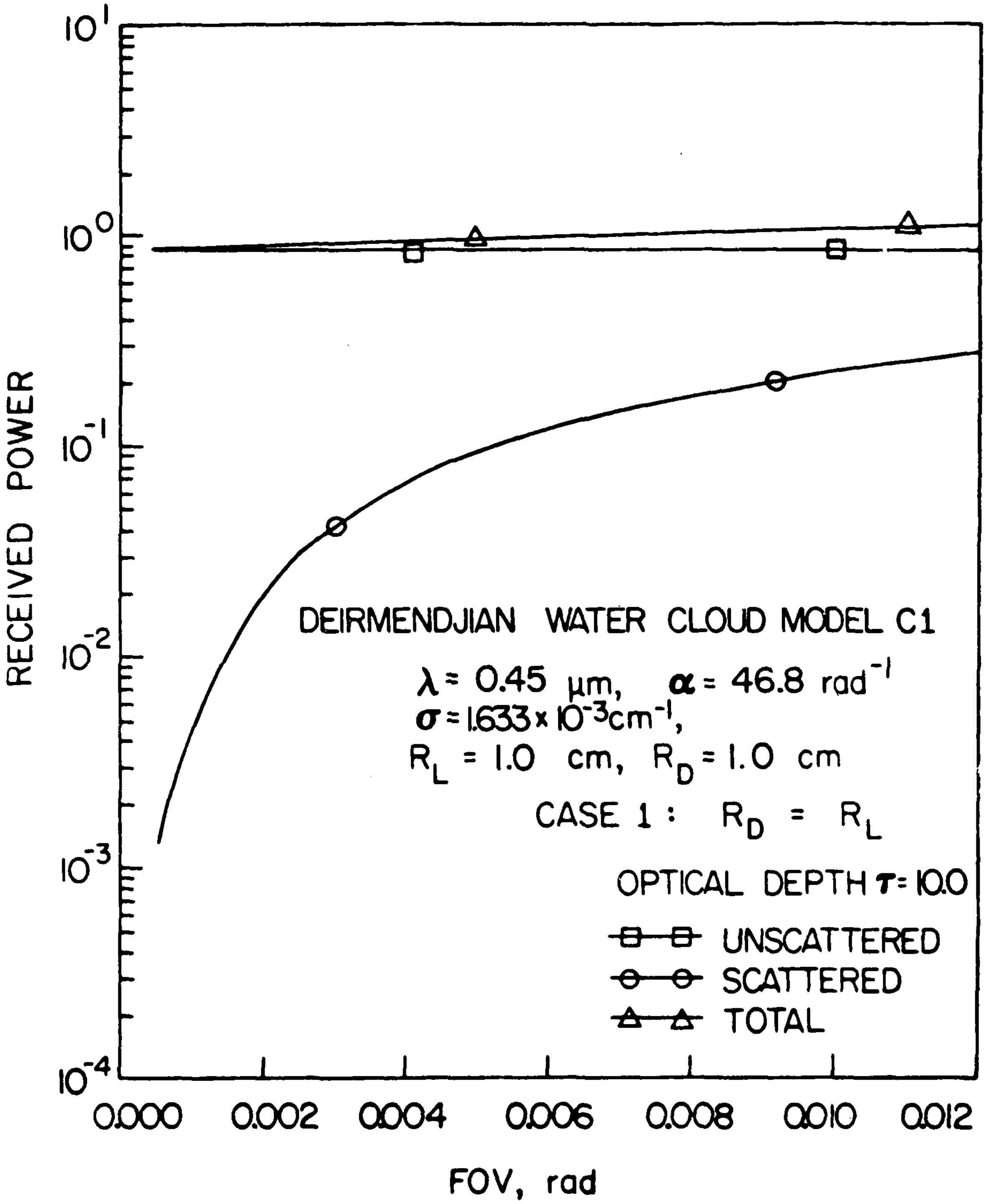

Figure 6. Received power (arbitrary units) on the beam axis as function of detector FOV corresponding to $\alpha = 46.80\ rad^{-1}$, $R_D = 1.0$ cm, and $\tau = 10.0$

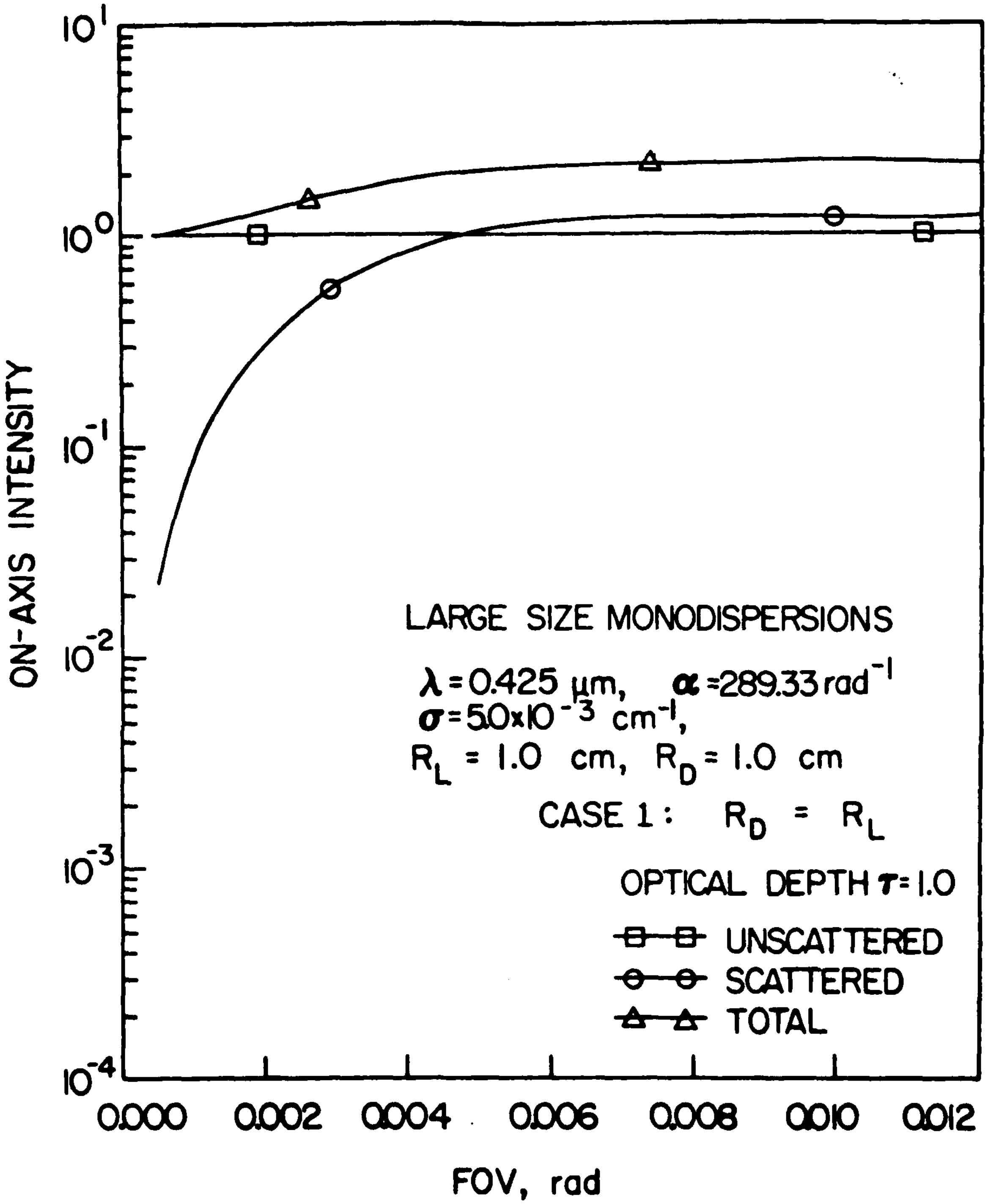

Figure 7. Normalized intensity on the beam axis as function of detector FOV corresponding to $\alpha = 289.33\ rad^{-1}$, $R_D = 1.0$ cm, and $\tau = 1.0$.

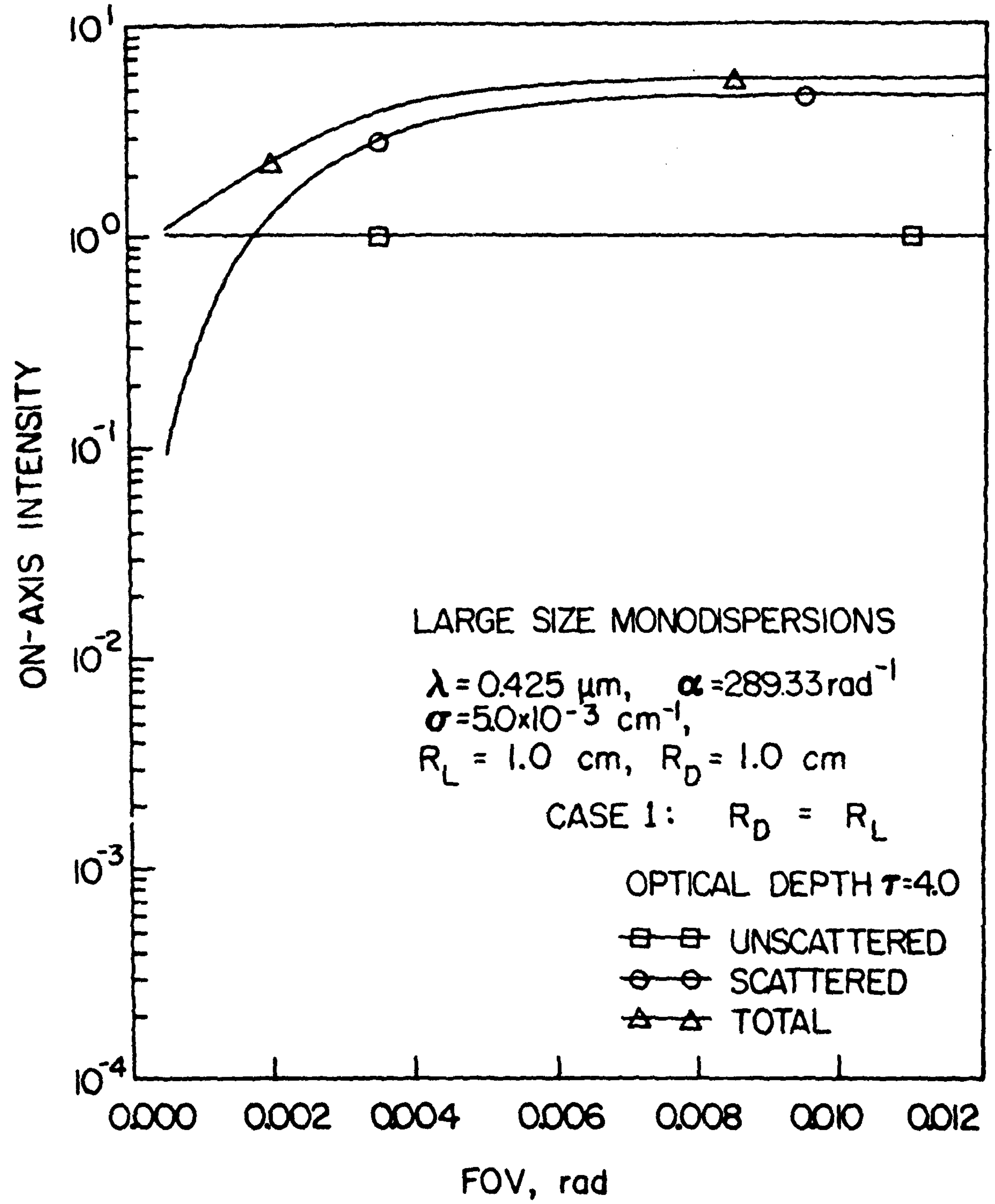

Figure 8. Normalized intensity on the beam axis as function of detector FOV corresponding to $\alpha = 289.33$ rad^{-1}, $R_D = 1.0$ cm, and $\tau = 4.0$.

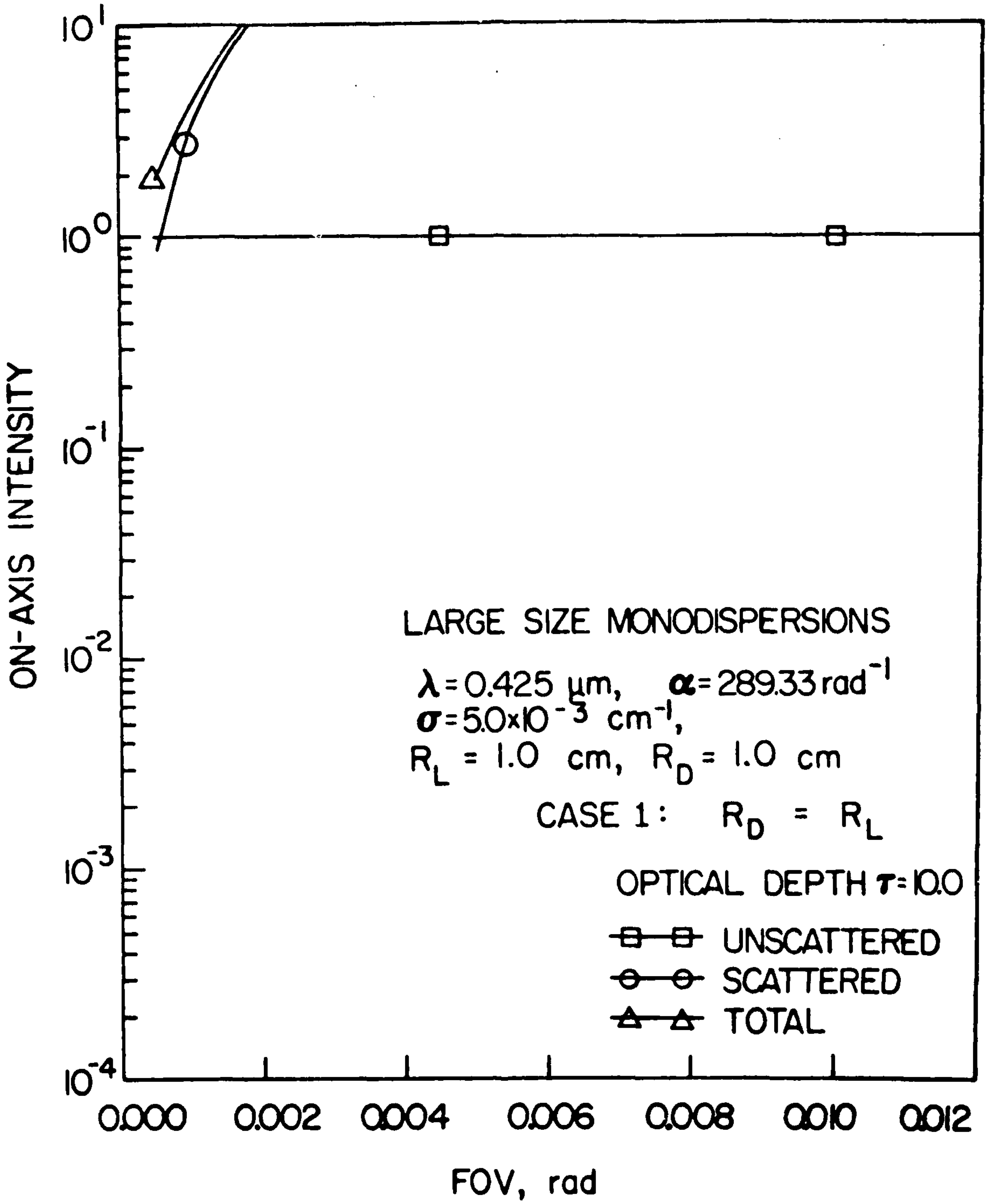

Figure 9. Normalized intensity on the beam axis as function of detector FOV corresponding to α = 289.33 rad^{-1}, R_D = 1.0 cm, and τ = 10.0.

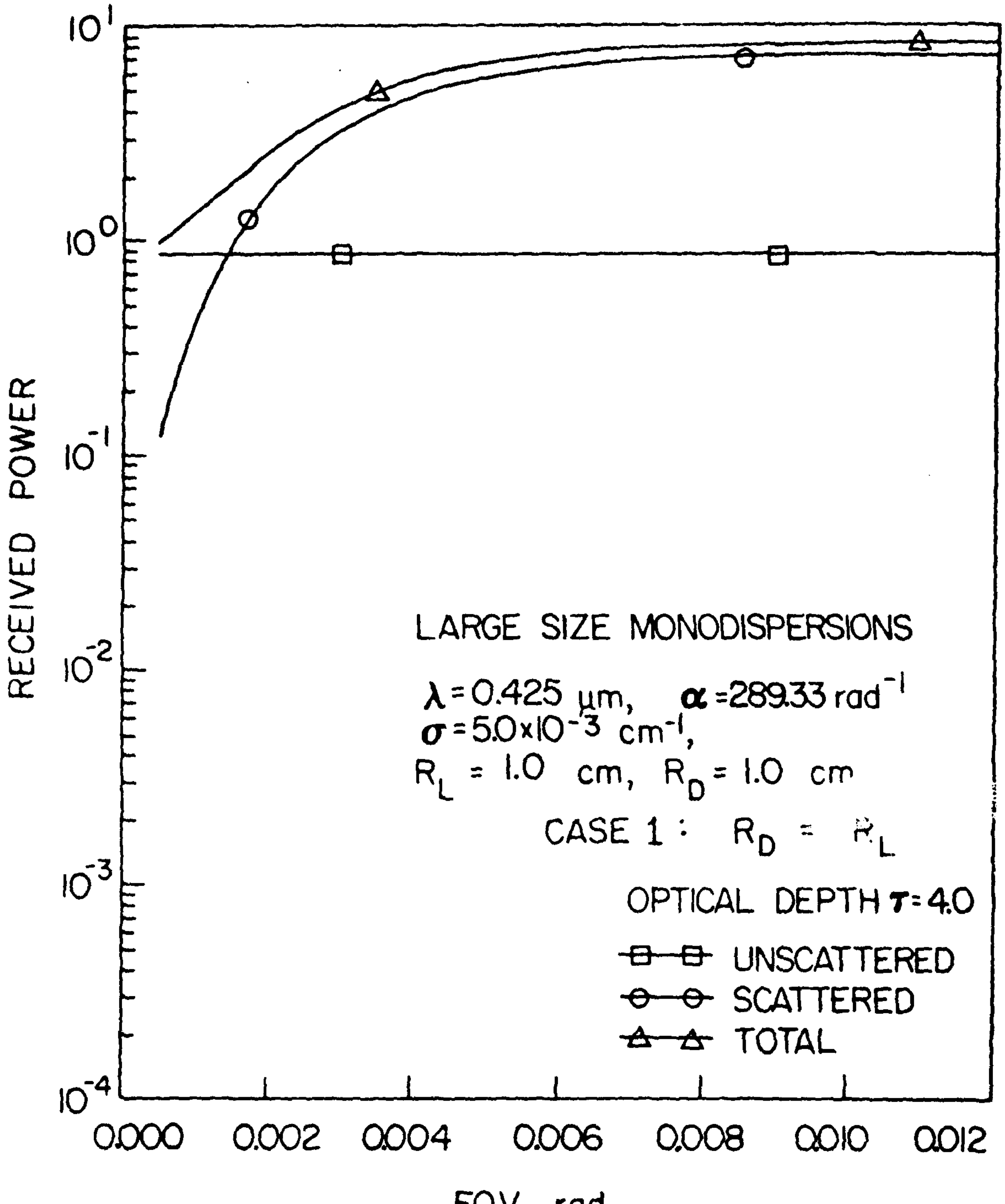

Figure 10. Received power (arbitrary units) on the beam axis as function of detector FOV corresponding to $\alpha = 289.33\ \mathrm{rad}^{-1}$, $R_D = 1.0$ cm, and $\tau = 4.0$ Received power is multiplied by $\exp(\tau)$.

$\sigma = 5.0 \times 10^{-2}\ cm^{-1}$ at $\lambda = 0.45\ \mu m$, for a coaxial detector of diameter $R_D = 1$ cm. Note that the phase function and the Gaussian fit to the forward lobe of the Mie phase function are plotted in Fig. 3 of Ref. 8.

In order to study the effect of the detector's radius R_D, we let R_D assume values smaller and larger than the beam diameter of the 1.0 cm, viz, $R_D = 0.2$ cm and 2.0 cm. Results were obtained for the same parameters as in the case of $R_D = 1.0$ cm. However, for the sake of clarity we present only the results for $\tau = 4.0$ for the two cases, viz, $R_D = 0.2$ cm (Figs. 11-12) and $R_D = 2.0$ cm (Figs. 13-14). Figures 11-12 depict the corresponding values of intensity and received power as functions of FOV for $R_D = 0.2$ cm, whereas, Figs. 13-14 depict the corresponding values for $R_D = 2.0$ cm. The three cases ($R_D = 1.0$, 0.2 and 2.0 cm; $\tau = 4.0$) for large particles with phase function parameter $\alpha = 289.33\ cm^{-1}$ show clearly the contrast in the behavior of the intensity and the received power.

The Fante-Dolin approximation employed in this paper enables one to estimate the corrections to the Bouguer-Beer law for a receiver having a finite field of view, as for example in Ref. 25.

VI. RECOMMENDATIONS

1. It should be noted that the small-angle approximation is valid for highly forward-peaked phase functions. It is, therefore, recommended that approaches be developed to deal with the case of MS in laser beams traversing small size aerosol particles, with broadly-peaked phase functions.

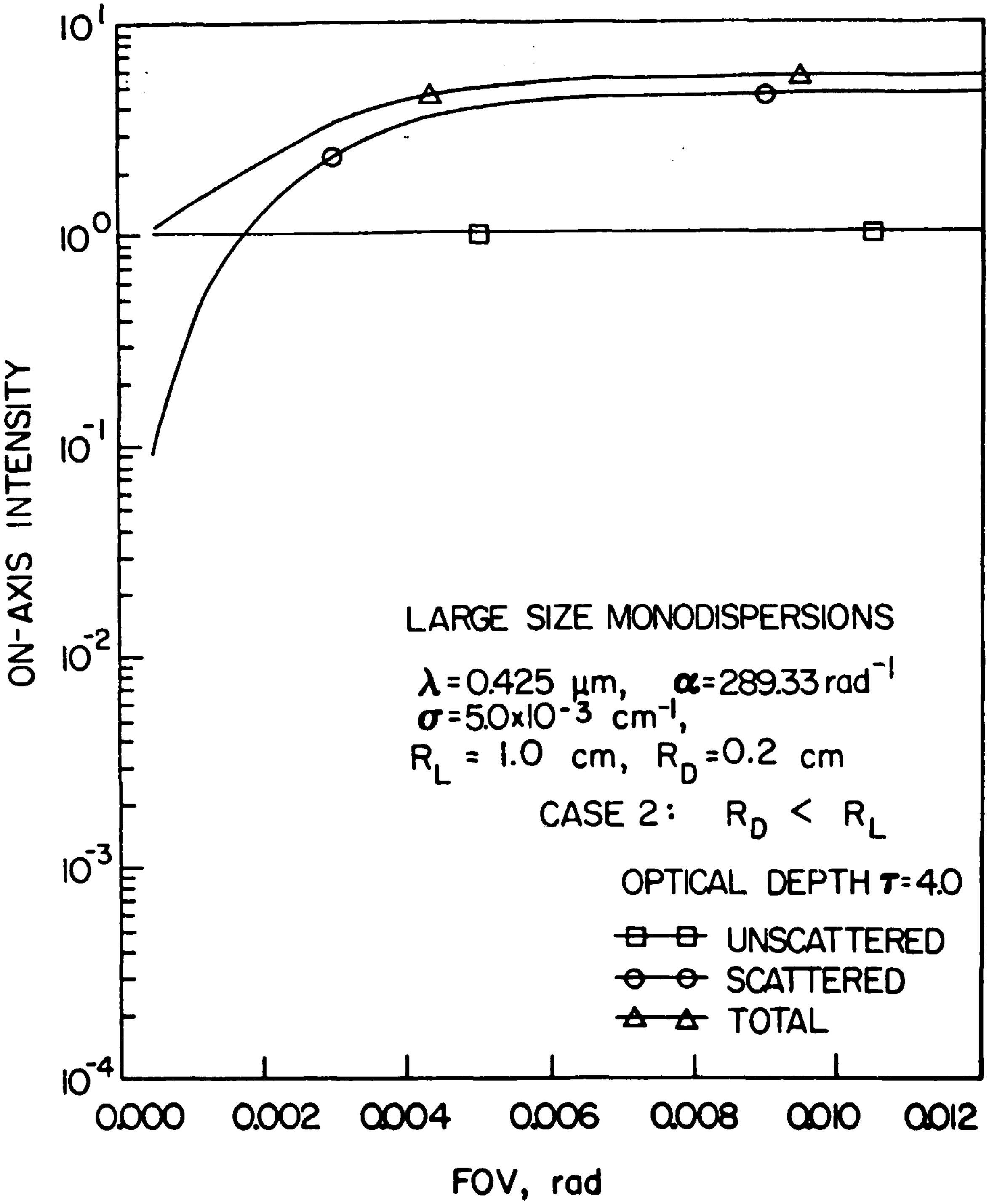

Figure 11. Normalized intensity on the beam axis as function of detector FOV for the same parameters as in Fig. 8 except $R_D = 0.2$ cm.

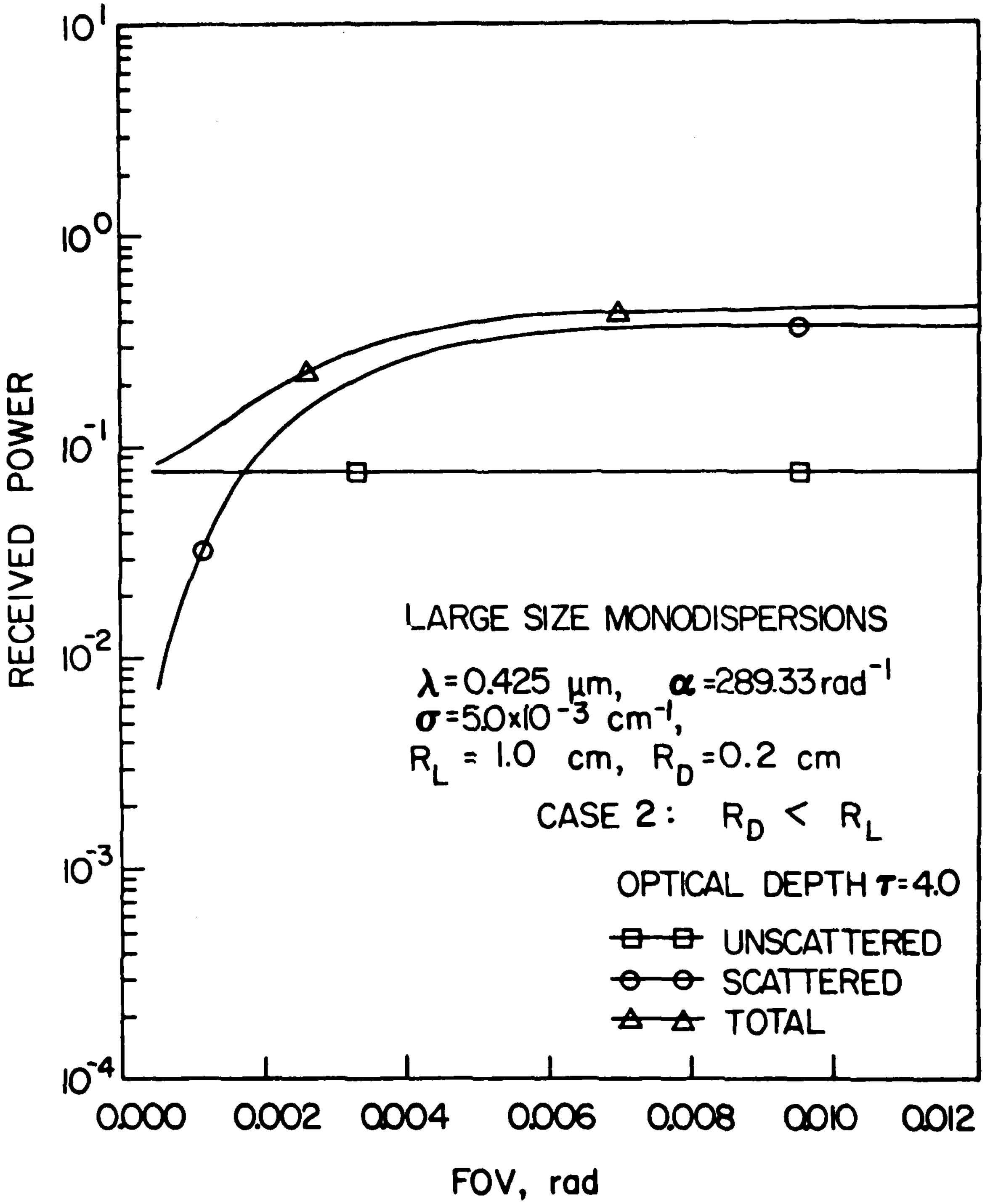

Figure 12. Received power (arbitrary units) on the beam axis as a function of detector FOV, for the same parameters as in Fig. 11. The received power is multiplied by exp (τ).

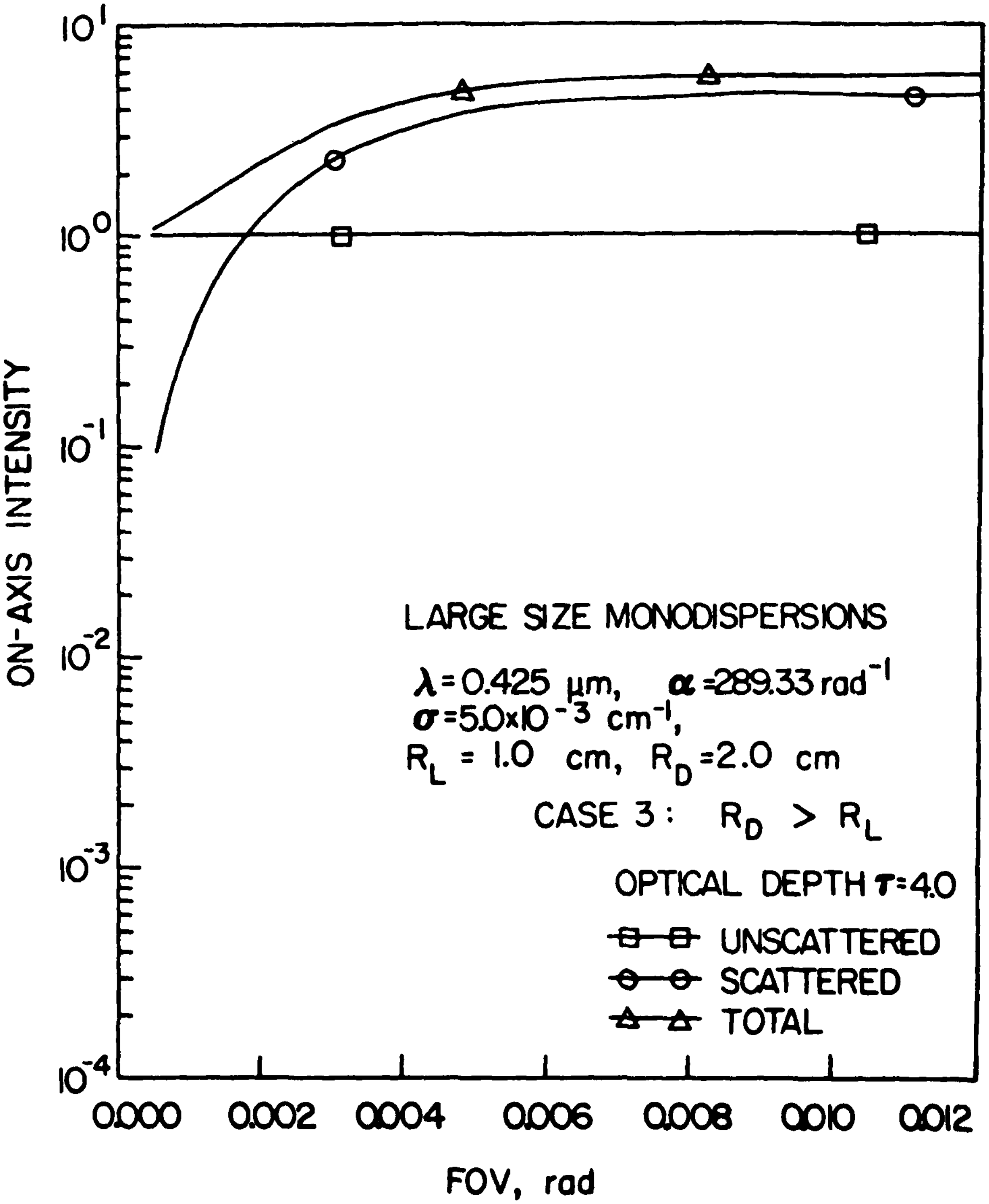

Figure 13. Normalized intensity on the beam axis as function of detector FOV for the same parameters as in Fig. 8 except R_D = 2.0 cm.

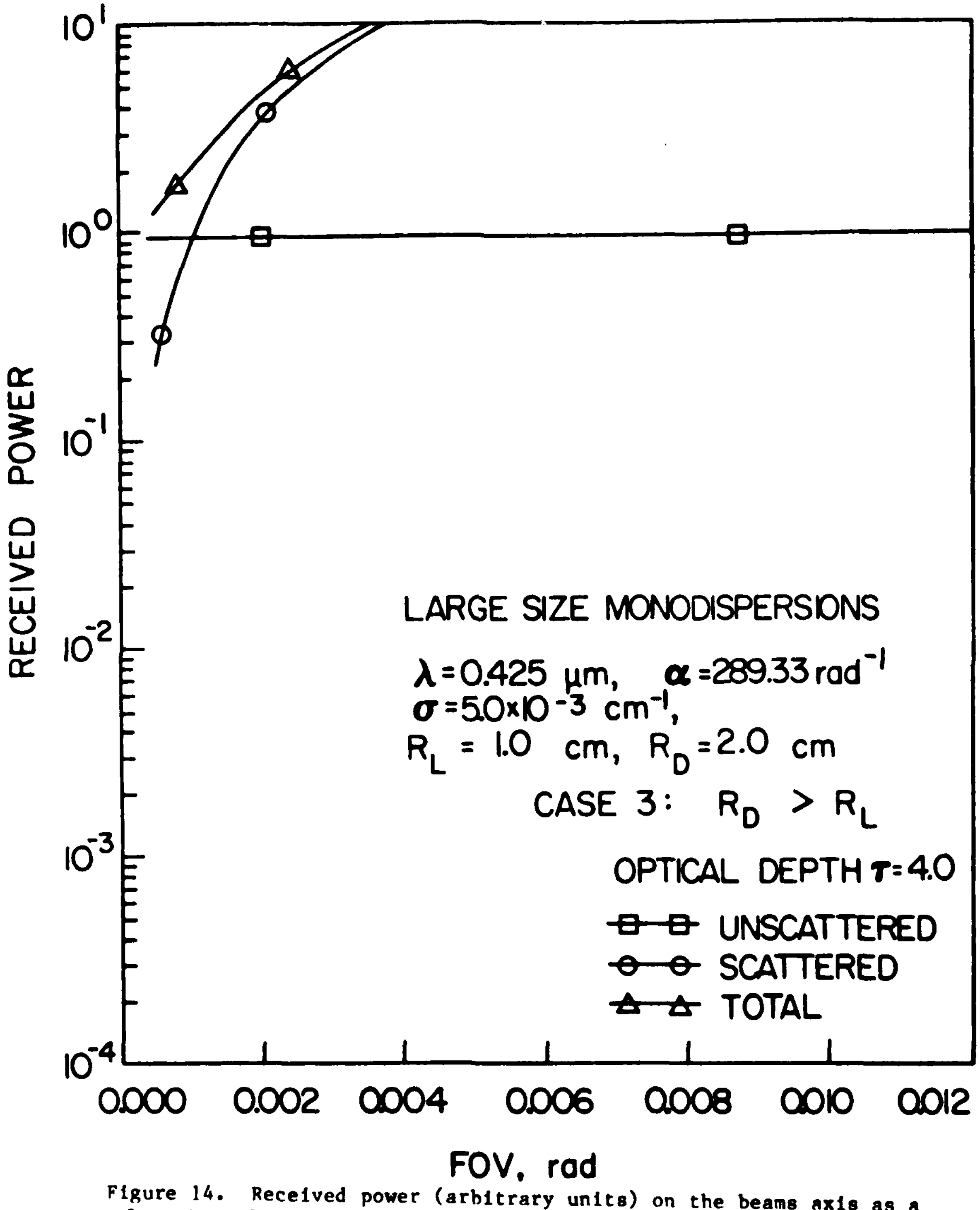

Figure 14. Received power (arbitrary units) on the beams axis as a function of detector FOV, for the same parameters as in Fig. 13. The received power is multiplied by $\exp(\tau)$.

2. It is recommended that experiments and numerical computations be performed to (a) determine the effects of the detector field of view on both the extinction and backscattering function measurements and (b) investigate the effects of beam diameter on optical extinction measurements.

3. It is recommended that the above investigation be repeated for the case of backscattering, which is of great importance for single-ended electro-optical systems.

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LITERATURE CITED

1. G. K. Goedecke, in EOSAEL 80, Vol. I, Technical Documentation, (L. D. Duncan, ed.), Atmospheric Sciences Laboratory Report ASL-TR-0072, January 1981.
2. E. A. Bucher, *Appl. Opt. 12,* 2391 (1973).
3. G. N. Plass and G. Kattawar, *Appl. Opt. 7,* 415 (1968).
4. W. G. Tam and A. Zardecki, *J. Opt. Soc. Am. 69,* 68 (1979).
5. A. Zardecki and W. G. Tam, *Can. J. Phys. 57,* 1301 (1979).
6. R. E. Jensen, *J. Opt. Soc. Am. 70,* 1557 (1980).
7. M. A. Box and A. Deepak, *J. Opt. Soc. Am. 71,* 1534 (1981).
8. A. Deepak, U. O. Farrukh, and A. Zardecki, *Appl. Opt. 21,* 431 (1982).
9. A. Deepak, A. Zardecki, U. O. Farrukh and M. A. Box, Proc. Workshop on Atmospheric Aerosols, Baltimore, MD 1979 (Spectrum Press, Hampton, VA) (1981).
10. A. Ishimaru, Proc. IEEE 65, 1030 (1977).
11. A. Ishimaru, *Wave Propagation and Scattering in Random Media,* Academic Press, New York (1978).
12. R. O. Gumprecht and C. M. Sliepcevich, *J. Phys. Chem. 57,* 90 (1953).
13. R. O. Gumprecht and C. M. Sliepcevich, *J. Phys. Chem. 57,* 95 (1953).
14. V. E. Zuev, M. V. Kabanov and B. A. Savelev, *Izv. Atm. and Oceanic Phys. 3,* 724 (1967).
15. A. Deepak and O. H. Vaughan, *Appl. Opt. 17,* 374 (1978).

16. A. Deepak and M. A. Box, *Appl. Opt. 17,* 2900 (1978).

17. A. Deepak and M. A. Box, *Appl. Opt. 17,* 3168 (1978).

18. L. S. Dolin, *Izv. V.U.Z. Radiofizika* 9, 61 (1966).

19. R. L. Fante, IEEE *AP21,* 750 (1973).

20. R. L. Fante, *J. Opt. Soc. Am. 64,* 592 (1974).

21. R. L. Fante, Proc. IEEE *62,* 1400 (1974).

22. R. L. Fante, Proc. IEEE *68,* 1424 (1980).

23. W. G. Tam and A. Zardecki, *Opt. Acta 26,* 659 (1979).

24. D. Diermendjian, Electromagnetic Scattering by Spherical Polydispersions, (American Elsevier, New York, 1969).

25. W. G. Tam and A. Zardecki, Appl. Opt. 21, 2405 (1982).

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